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Novel Amalgams for in-Space Parts Fabrication

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Premise

- Replacement parts will likely be necessary during extended deep space missions.
  - Repair parts increase vehicle weight and take up precious cargo space
  - What will break cannot be anticipated
  - Fabricating parts can include complicated procedures
    - Handling and pouring of hot liquid metal
    - Complicated machining and fluid handling

Amalgam

- **Amalgam: An alloy of mercury with at least one other metal.**
- **Amalgams are based on a peritectic reaction:**

  ($S_1 + L_1 \rightarrow S_2$)

  Dental amalgams are well-understood and have an established application.

Amalgam Considerations

- Room temperature processing
- Corrosion resistant
- Minimum: power consumption, crew interaction, final finishing, and mass/volume consumption
- Moldable
- Net-shape part (no shrinkage or additional machining)
- No fluid handling issues (hot liquid metal)

Amalgams have potential for fabricating parts during deep space missions.

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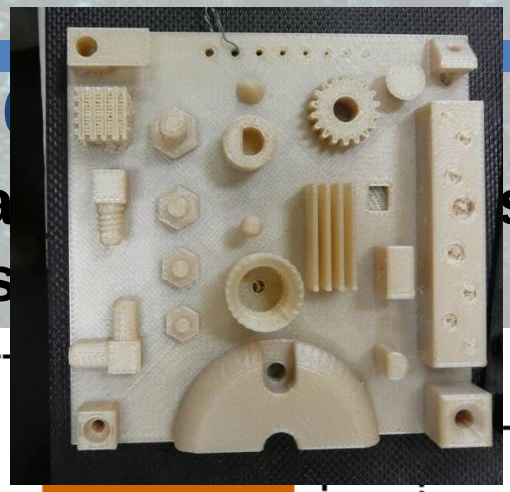
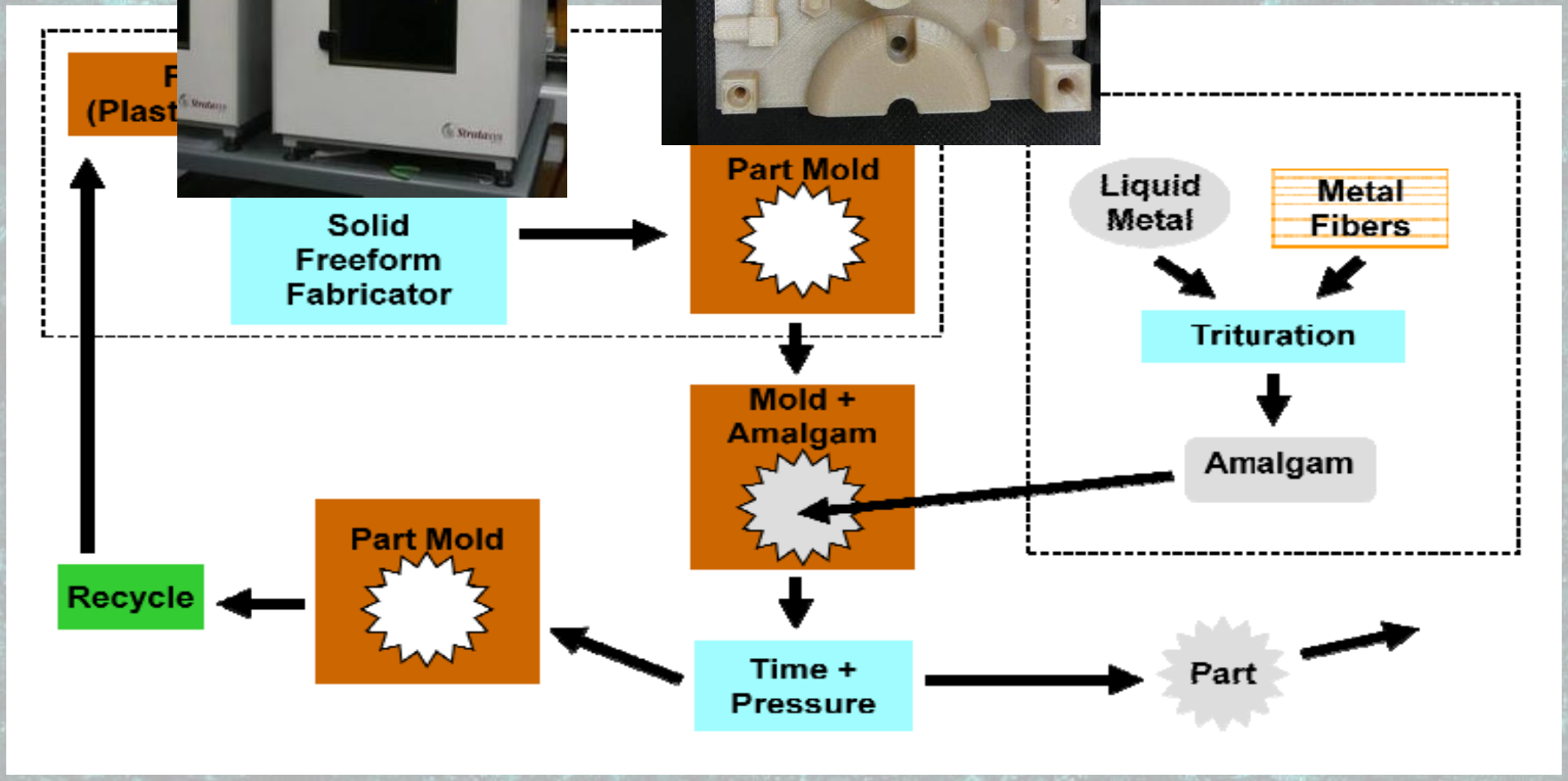
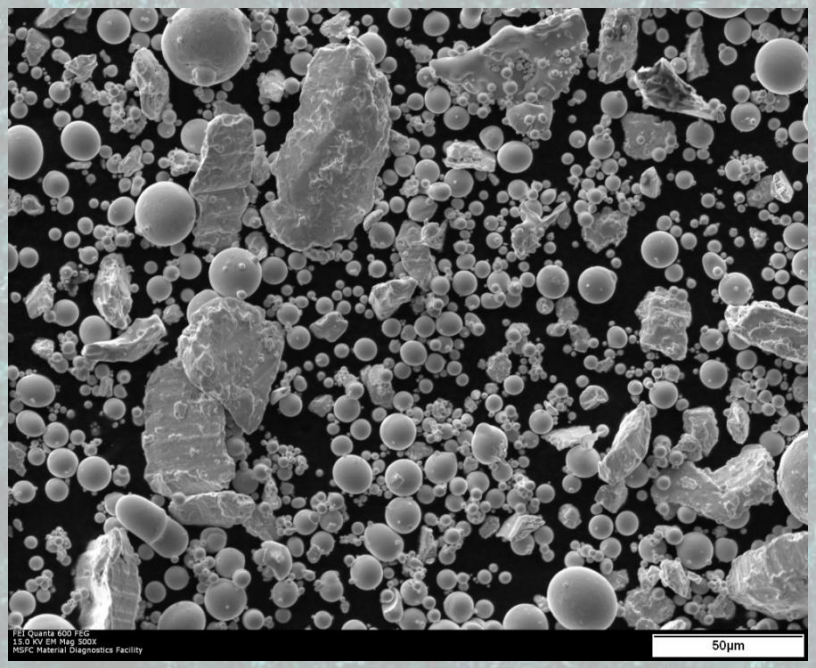




Amalgam Disadvantages

Mercury, which is toxic, is typically used

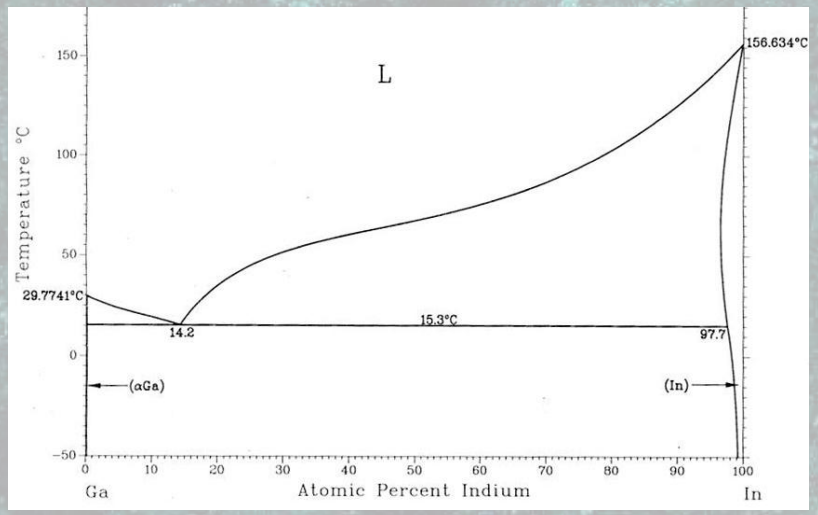
Amalgams have low tensile strengths (~10% of compression)

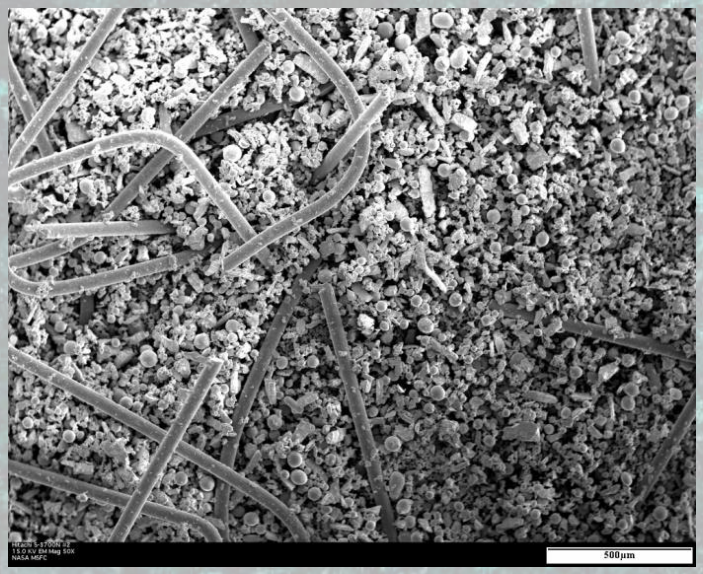


Cu-Ag-Sn Amalgam Powder Consisting of Atomized Spheres and Lathe-cut Particles

Solutions to Disadvantages

Substitute Ga-In liquid for Hg





Include high-strength steel fibers with commercial Ag-Sn-Cu powder

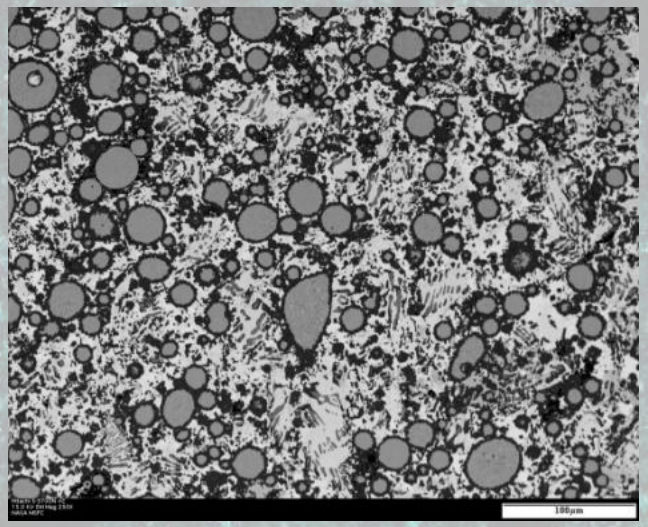
Research Objective

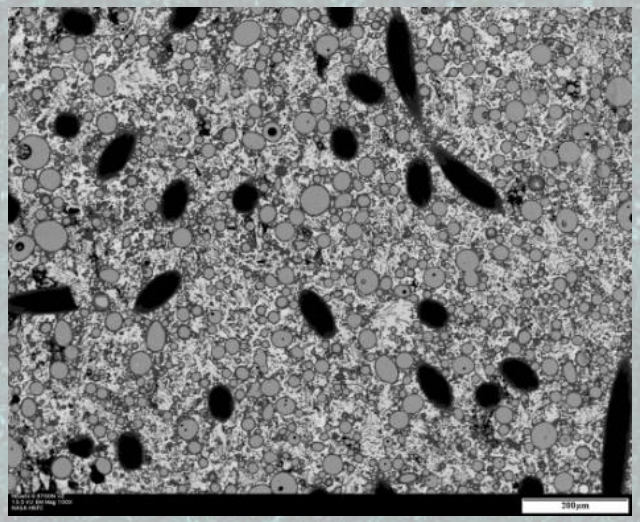
Can Ga-In liquid substitute for Hg?

Will the inclusion of steel fibers improve the mechanical properties of amalgams?

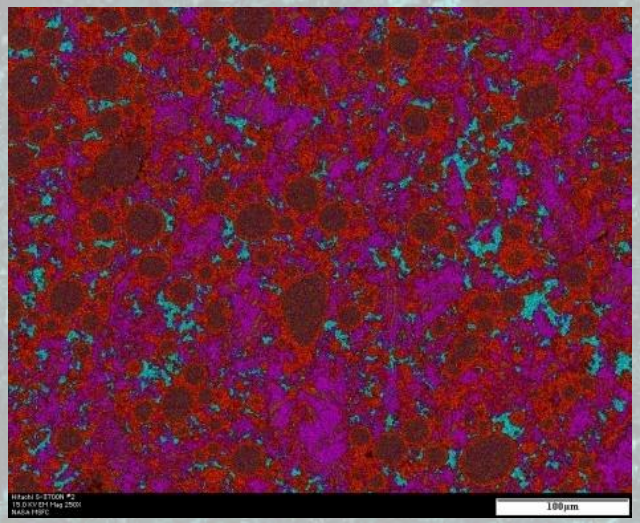
SEM micrographs of processed samples with and without fibers

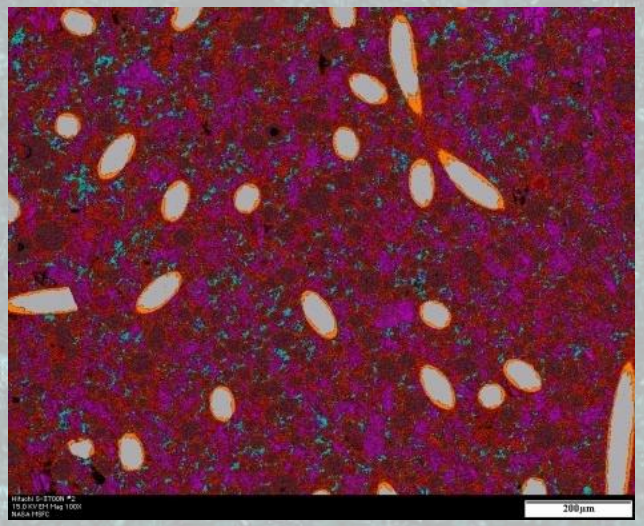
Dense fully reacted amalgam with no porosity in both cases.





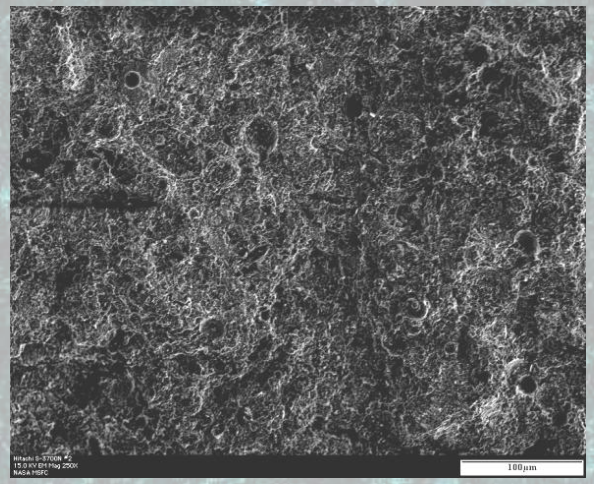
Color key:
Turquoise = tin,
Indium = green,
Silver = purple,
Gallium = red,
Iron/steel = grey,
Copper = orange



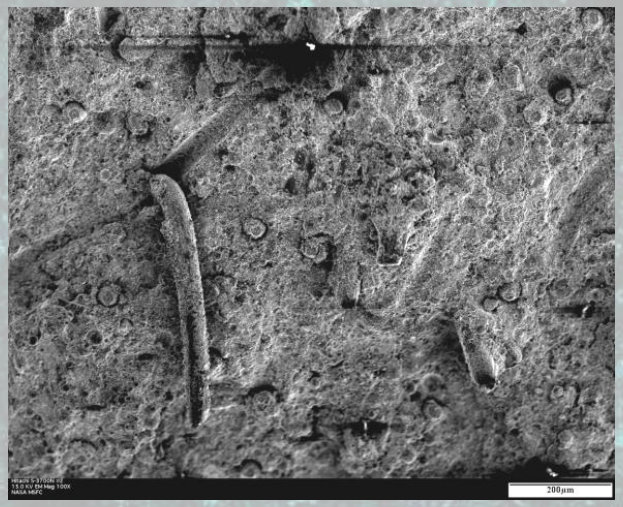


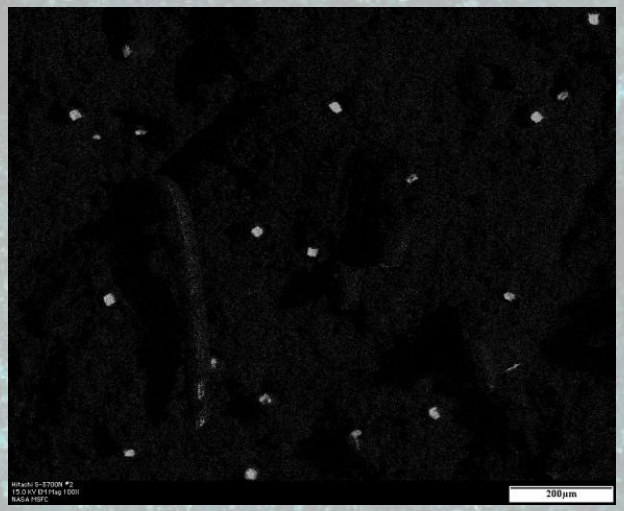
Fracture Surfaces

A typical amalgam (no fibers) fracture surface



A fracture surface of an amalgam with steel fibers

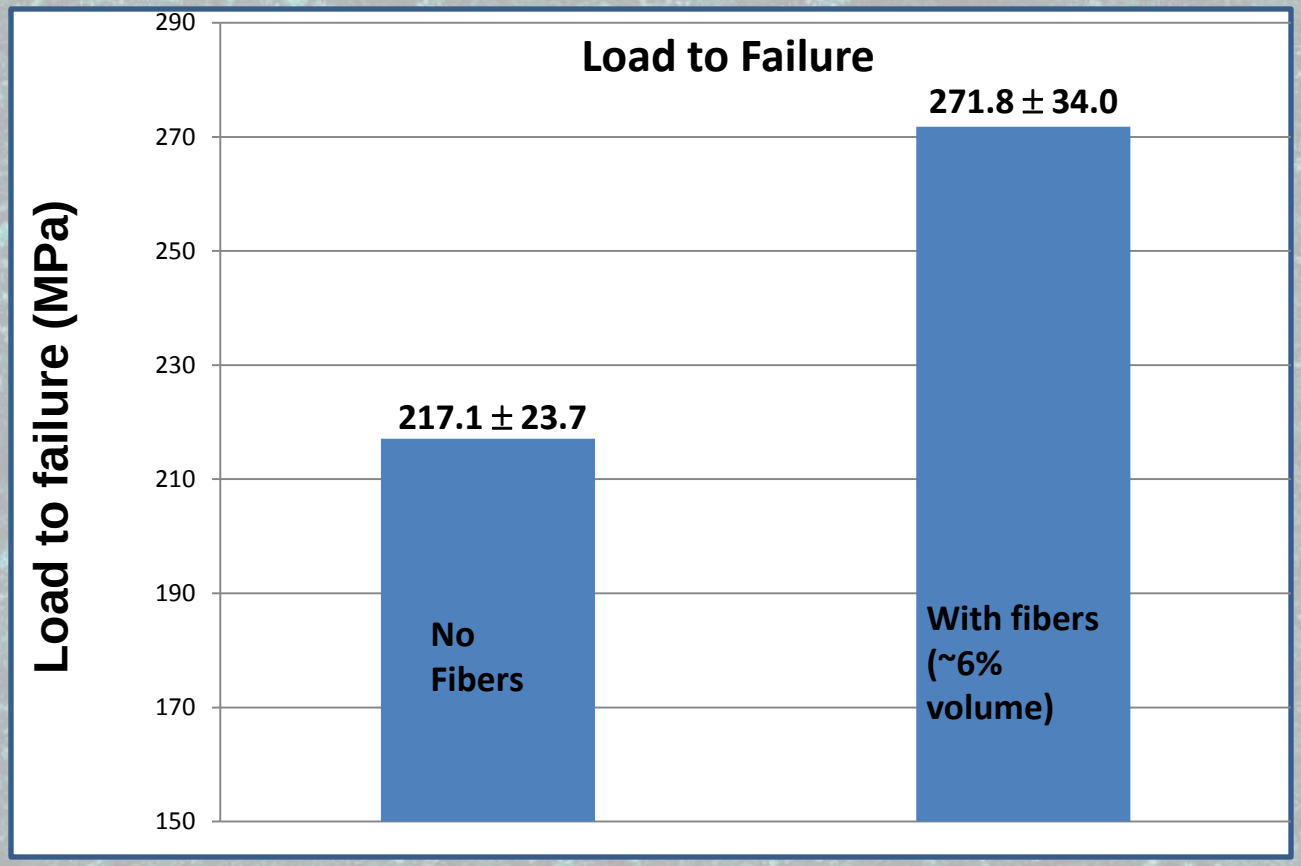




A phase map showing the distribution of steel fibers

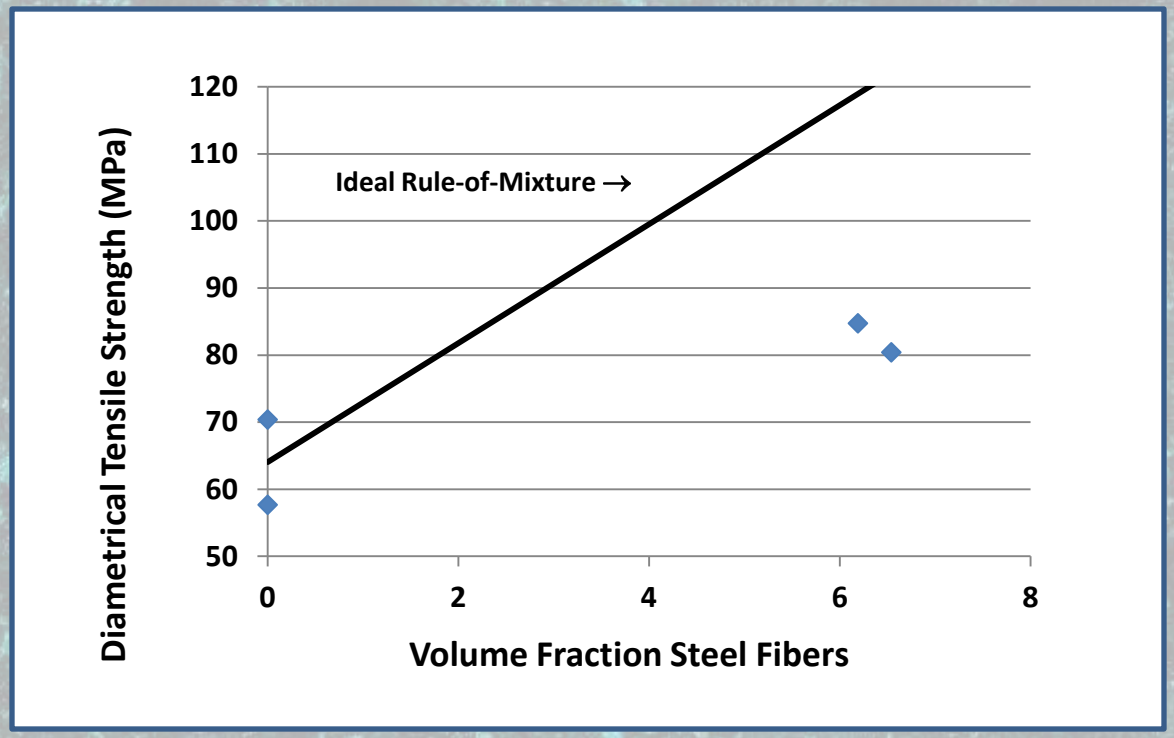
Mechanical Testing: Load to Failure

A comparison of the load to failure (crush) strength of amalgams without fibers and those with.



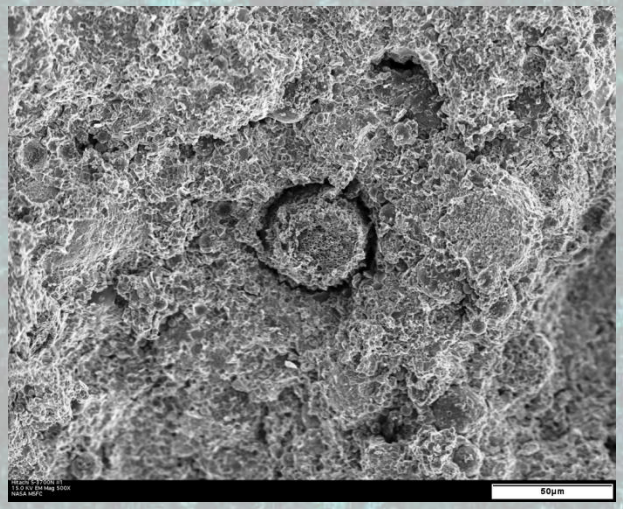
Samples with included steel fibers performed better

Mechanical Testing: Diametrical Tensile Strength

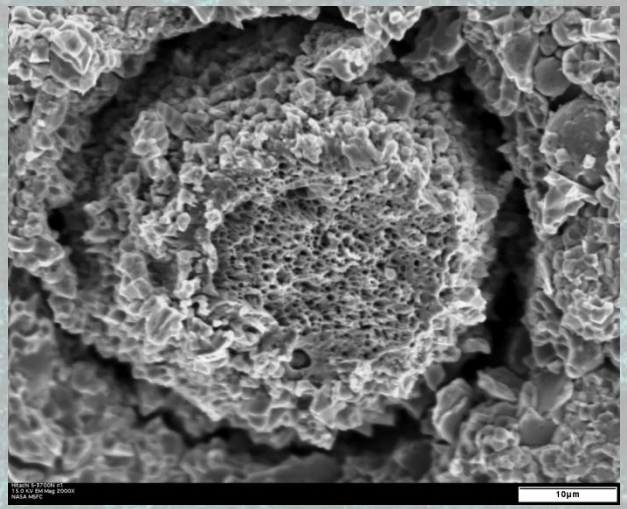


Samples with included steel fibers again performed better

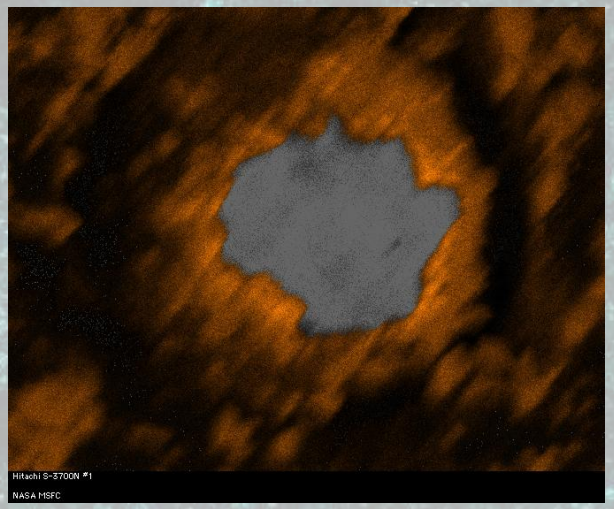
Role of Steel Fibers



Micrograph of a broken steel fiber (center) in the amalgam matrix.



Higher magnification showing the dimpled fracture surface of the steel fiber surrounded by reaction products.



Elemental phase map showing the extent of steel (gray color) after necking, ~36% reduction in area.

Mechanical properties increase due to the steel wires inherent strength, its bonding with the matrix, and subsequent plastic deformation prior to failure.

Conclusions

- Sound amalgams can be fabricated by substituting Ga-In liquid for mercury; Cu-coated steel fibers bond well with the amalgam components.
- Inclusion of steel fibers significantly improved mechanical properties.
- An application scenario utilizing amalgams for in-space parts fabrication and repair was suggested.
- Procedure and materials need to be optimized.

Acknowledgments

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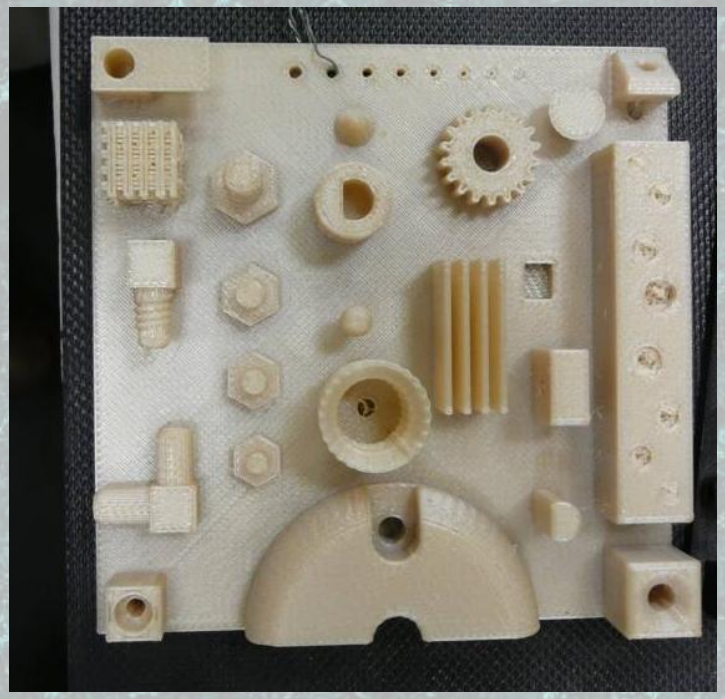
Backup Slides

Outline

- Introduction
  - Premise
- Amalgams
  - Advantages/Disadvantages/Solutions
  - Scenario applications
- Experiment
  - Objective
  - Process
  - Results: Microstructures, Fracture Surfaces, Mechanical Testing, Modeling
- Future work and Conclusions

Molding

In order to create spare parts, molds can be made by a Fused Deposition Modeling machine and filled with amalgams.

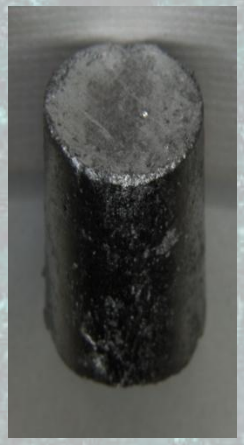


Examples of shapes made by a FDM

Fused Deposition Modeling machine

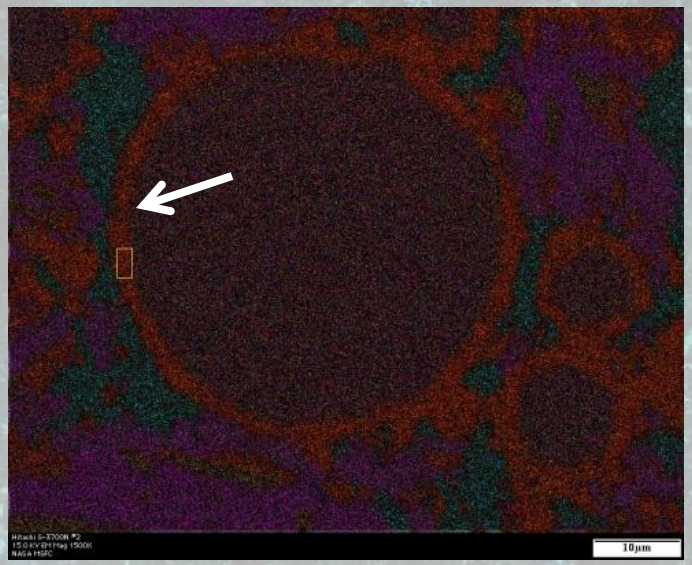
The Process

- Determine and weigh out amalgam components.
- Place components in plastic capsule and mechanically mix.
- Insert newly reacted amalgam in quartz cylinder between two quartz pistons, compress in clamp, and leave overnight.
- Mechanically test sample using a laboratory press to determine load to failure or diametrical tensile strength.
- Evaluate microstructure.

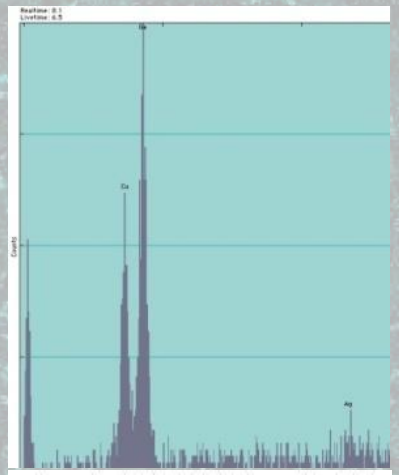


Amalgam Reactions: Intermetallic Compounds

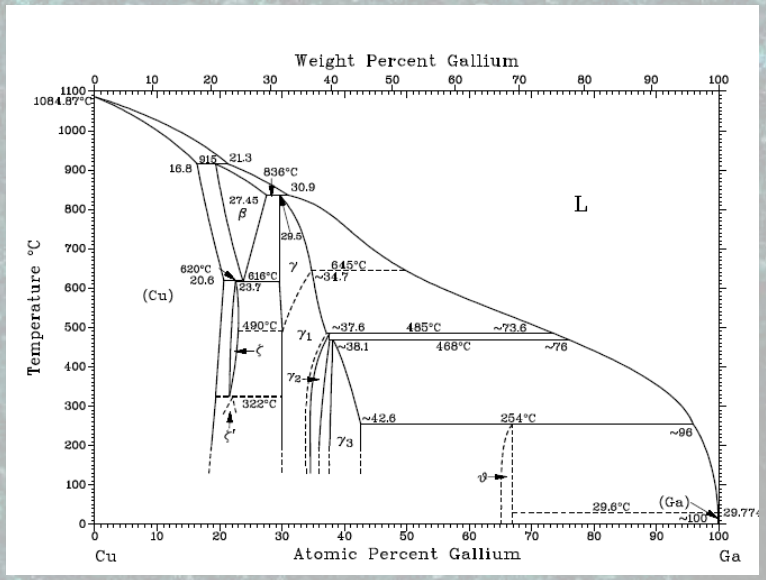
SEM phase maps and extracted spectrums can be used to predict compounds formed within amalgams.



Phase map showing a reaction product around a Ag-Sn-Cu particle.

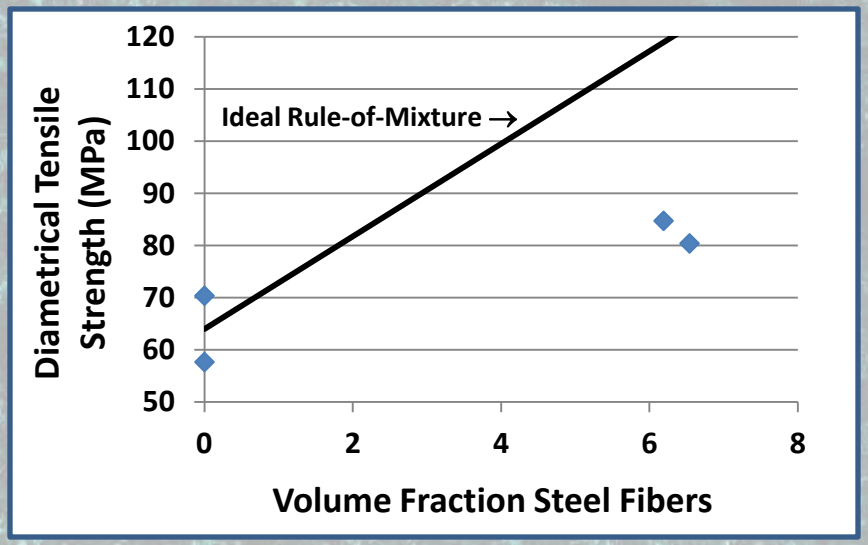


Element	Weight %	Std. Dev.	Atomic %
Cu	26.92	7.81	30.09
Ga	61.26	17.10	62.42
Ag	6.58	2.74	4.33
In	1.10	1.09	0.68
Sn	4.15	2.46	2.49
Total	100.00		



Cu-Ga phase diagram

Mechanical Testing: DTS



Samples with included steel fibers performed better

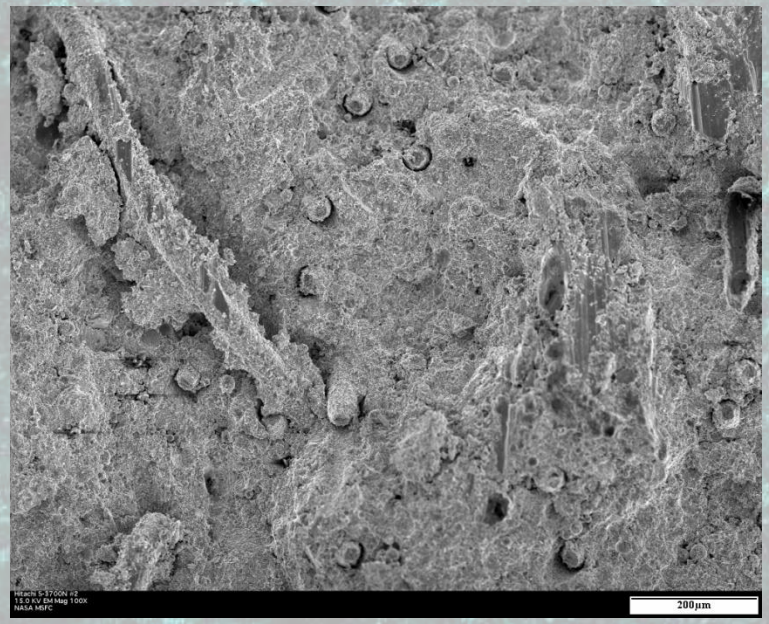
The rule-of-mixtures was applied to predict optimal tensile strength. The formula is as follows:

$$\delta_{co} = \chi V_f \delta_f + V_m \delta_m$$

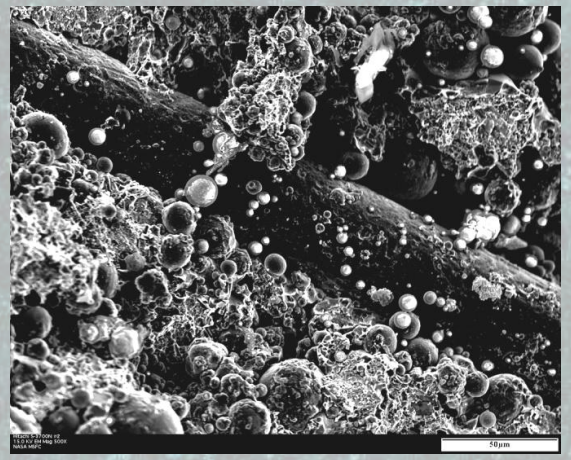
Note that δ_{co}, δ_f , and δ_m are the ultimate strengths of the amalgam, fibers, and matrix(everything but the fibers), respectively. Note that V_f and V_m are the volume fractions of the fiber and matrix and that χ is a constant which considers fiber orientation and length factors.

Sample Preparation Problems

Good processing with good microstructure resulting in good properties. Well coated fibers.



'Crumbly' lack of bonding between fibers and powder, due to insufficient liquid



'Bunched' fibers, poor mixing precludes any reaction

Future work

Materials and processing parameters need to be optimized in order to maximize material properties. These include, for example:

- Fiber lengths and volume fractions
- Mixing techniques
- Reaction/setting time (not too fast)

Steps toward preparing larger samples should also be taken.